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Review

Wave spectral finite element model for the prediction of sound transmission loss and damping of sandwich panels

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ABSTRACT

Sandwich panels are usually modeled by considering only asymmetric motion which assumes the core deforms by transversal shearing without any compressive deformation over the thickness. This assumption is acceptable for panels with relatively stiff and thin cores. However, symmetric motion becomes important when the core is thick or soft. Under such conditions, the compressive deformation over the core thickness becomes significant. This paper addresses the prediction of the Sound Transmission Loss (STL) and composite Damping Loss Factor (DLF) of sandwich panels with either thin or thick cores as well as stiff or soft (viscoelastic) cores. Both the skin and the core are assumed to be orthotropic. A spectral finite element based approach is developed wherein the stress and strain components in each layer are described using the properties in that layer for a forced trace wave number and heading direction. The proposed approach provides a reliable and numerically efficient tool to account for the compressive deformation effect of thick orthotropic sandwich layers. Moreover, the proposed model is also able to consider panels with multiple of layers with varying properties.

Contents

1. Introduction

Sandwich panels with either thin or thick skins and stiff or soft (viscoelastic) cores where both the skin and the core can be composed of various orthotropic layers (laminates) are used a variety of engineering applications with considerable interest in the estimation of the Sound Transmission Loss (STL) and composite Damping Loss Factor (DLF) of sandwich structures.

For cases when the dilatational motion of composite and sandwich layers' can be neglected, the estimation of the STL is well understood [1]. A theoretical approach accounting for an

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incompressible core and providing an estimate of the asymmetric propagating motion has been developed by Kurtze and Watters [2]. The sound transmission of sandwich plates with an isotropic compressible core has been studied by Ford et al. [3]. The theory was later refined and applied by Smolenski and Krokosky [4] to investigate the influence of the core properties on the dilatational natural frequencies. Mathematical expressions of the impedances related to asymmetric and symmetric propagating motion for isotropic sandwich panels have been presented by Dym and Lang [5] and used to predict the transmission loss. Later a generalization of the theory for asymmetric sandwich panels with orthotropic core was also presented [6]. Unidirectional sandwich panels with isotropic and orthotropic compressible cores have been studied in a sound transmission loss context by Moore and Lyon [7]. The consistent high-order approach described in [8] has been used by Wang et al. [9] for the derivation of the sound transmission loss in symmetric unidirectional sandwich panels with isotropic skins, and either honeycomb and isotropic core. Transmission loss predictions have been successfully compared with experimental data. The transmission loss of laminate and sandwich composite shells and plates has been studied by Ghinet et al. [10–13]. A Discrete Layer Modeling (DLM) approach was presented and these theories have been shown to apply well for sandwich structures with a relatively stiff core where dilatational motion is not perceptible at the audible frequencies of interest. This model was recently updated by Ghinet and Osman [14] in order to account for symmetric and asymmetric modes of motion and incorporated in a TMM framework [15] to predict the STL of sandwich composite structures with visco-elastic and porous treatments.

Unlike the STL problem, the work on the prediction of the DLF is limited to few methods. Pagianakos and Saravanos [16], developed a FE based model to predict the damping of laminated shell composite structures. The authors assumed a simple displacement field through the thickness and used low order polynomials for each finite element. The model provides a good description of the structural acoustic behavior of laminates at low frequencies. However, at high frequencies where the wave length of excitation is small compared to the cross sectional dimension, the model become inaccurate [17]. Kerwin and Ungar [18,19] investigated the DLF of laminate panels with visco-elastic layers. A low order displacement field was assumed to describe the cross sectional response of the laminate. The accuracy of the model [18,19] was limited by the assumptions used in the description of the displacement field. In order to provide a good description of the structural – acoustic response, the Statistical Energy Analysis (SEA) method has been used by many authors [21,22]. The accuracy of the SEA method is interrelated to the accurate prediction of vibro-acoustic indicators such as the DLF. The Transfer Matrix (TM) Method is also routinely used to address the modeling of layered structures [23]. Although this method is accurate for sandwich with thin and thick cores it is limited to isotropic cores. Recently, Shorter [17] developed an alternative to the transfer matrix method based on a one-dimensional Finite Element Method to predict the DLF of viscoelastic laminate structures. Again, the model was accurate but limited to isotropic cores, and furthermore, the model was computationally expensive due to the inversion of large matrices as a result of an increasing number of elements in the cross sectional thickness. Some publications dealt with coupled FE/BE methods to analyze sandwich structures with embedded visco-elastic layers. It is noted here, that both the STL and DLF problems can be solved accurately using the FE and BE methods as described in Refs. [24–26].

In this paper, the wave spectral finite element method (WSFEM) is applied. Although this method has been in existence for a long time under the name of the dynamic stiffness method, its use was limited to simple vibration studies. This method is a merger of the direct dynamic stiffness method [33–35] and the finite element displacement method [36]. Elements are formulated and assembled as in the standard FEM while the base functions are the frequency dependent local solutions of the equations of motion. It is only recently that the potential of this method to handle a wide range of applications has been realized [26,27]. For instance, this method was used to analyze the stationary vibrations in a beam and plate structure [28,29]. Finnveden [30] used the WSFEM to analyze the stationary vibrations in a railway car structure. WSFEM was also applied to analyze the vibration of straight fluid-filled pipes with flanges [31]. In Ref. [32] the wave-guide finite element method was used to calculate the wave propagation characteristics for built up thin-walled structures. Compared with the standard FEM, the wave spectral finite element method allows a reduction of the number of d.o.f., while increasing the accuracy. The FE formulation increases the applicability of the dynamic stiffness method since standard FE approximations can be incorporated. Moreover, the routines for calculating the dynamic stiffness matrices when base functions are exponential functions, originally developed in Ref. [30] considerably reduces the efforts in the element formulation. In addition when compared to the classical transfer matrix method [23] or the DLM [14], the present approach allows quick and accurate estimation of STL and composite damping of thick orthotropic and composite solids without the assumption of through thickness incompressibility. This is for instance important for sandwich composite panels with thick orthotropic core (e.g. Honeycomb core). The classical TMM with solid elements mainly handle isotropic layers, while for the DLM, two computations are needed one for the symmetric motion and the second for the anti-symmetric motion, as explained in Ref. [14].

The aim of this paper is to deal with the estimation of the Sound Transmission Loss (STL) and composite Damping Loss Factor (DLF) of sandwich panels. Panels with either thin or thick skins and a stiff or soft core are studied. In addition, both the skin and the core can be fabricated from various layers (laminates). The method is based on spectral finite element method, wherein the stress and strain components at the two faces of a layer are described using the properties of the medium of the layer for a forced trace wave number and heading direction. The model accommodates sandwich structures with a thin or thick core as well as a stiff or soft core as found in the case of constrained layer damping. Moreover, both the skins and the core are assumed to be orthotropic. While the paper concentrates on sandwich panels, the proposed model is valid for panels with any number of layers. In this work, the method is used to predict the STL and the DLF of various sandwich panels. Comparison with numerical methods (FE/BE), other classical models and experimental data are presented to demonstrate the validity of the model.

2. Derivation of the model

2.1. Wave-based description of the stress-displacement relation in an elastic solid

Consider a flat elastic solid with infinite lateral extent in the $x - y$ plane. Its thickness is thus measured along the z direction. Under the assumptions of linear elastodynamics, the equilibrium equations of the elastic solid are given by:

$$\begin{aligned}
&\partial\sigma_{xx}/\partial x + \partial\sigma_{xy}/\partial y + \partial\sigma_{xz}/\partial z = \rho\ddot{u},\\
&\partial\sigma_{yy}/\partial y + \partial\sigma_{yz}/\partial z + \partial\sigma_{xy}/\partial x = \rho\ddot{v},\\
&\partial\sigma_{zz}/\partial z + \partial\sigma_{xz}/\partial x + \partial\sigma_{yz}/\partial y = \rho\ddot{w}.
\end{aligned} \tag{1}$$

Here ρ denotes the mass density, σ_{pq} with $p, q = x, y$, the components of the stress tensor; $\{u, v, w\}$ are the three displacement components in $x,\ y$ and $z$directions.